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This AASERT program was originally under the direction of Prof. J. Paterson in 1999, this program was transferred to Prof Charles Kruger and the focus shifted to "Graduate Research Training on Air Plasma Diagnostics" in the framework of the "Air Plasma Ramparts" MURI research program entitled "Mechanisms of Ionizational Nonequilibrium in Air Plasmas," Two graduate students, Kate Snyder and Jonathan Flad, supported by this program have received training on temporally and spatially resolved Cavity Ring-Down spectroscopy measurements of electron density in a pulsed atmospheric pressure nitrogen plasma. They have contributed also to the ongoing development of CRDS measurements of NO4 concentrations in an air plasma produced with radio-frequency inductively coupled plasma torch.

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THERMOSCIENCES DIVISION

Development of a Pulsed 2 Gigawatt, 5 Kilojoule FEL Source at L-Band

Final Technical Report
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Professor Charles H. Kruger
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Graduate Research Training on Air Plasma Diagnostics

The AASERT program entitled "Development of a Pulsed 2 Gigawatt, 5 Kilojoule FEL Source at L-Band" was originally under the direction of Prof. J. Paterson of the Stanford Linear Accelerator. In 1999, this program was transferred to Stanford University under the direction of Prof. Charles Kruger and the focus shifted to "Graduate Research Training on Air Plasma Diagnostics" in the framework of the "Air Plasma Ramparts" MURI research program entitled "Mechanisms of Ionizational Nonequilibrium in Air Plasmas," with Prof. Charles H. Kruger as the Principal Investigator and Dr. Robert J. Barker (AFOSR) as Technical Monitor. Two graduate students, Kate Snyder and Jonathan Flad, supported by this program have received training on temporally and spatially resolved Cavity Ring-Down spectroscopy measurements of electron density in a pulsed atmospheric pressure nitrogen plasma. They have contributed also to the ongoing development of CRDS measurements of NO^+ concentrations in an air plasma produced with a radio-frequency inductively coupled plasma torch. Because NO^+ tends to be the dominant ion in weakly ionized atmospheric pressure air plasmas, its concentration is close to the concentration of electrons. Therefore this diagnostic technique has the potential of providing one of the most direct measurements of electron concentrations in atmospheric pressure air plasmas.

The intent of the parent Air Plasma Ramparts program is to investigate energy efficient methods for creating and sustaining large volume atmospheric air plasmas with electron number densities of the order of 10^{13} cm^{-3} that can be employed to shield aircrafts or other sensitive components from electromagnetic radiation. The equilibrium concentration of electrons in low temperature atmospheric pressure air is extremely small, typically on the order of 10^6 cm^{-3} at 2000 K. In order to produce the required electron concentrations with reasonable energy expenditures, it is necessary to add energy to the plasma in a targeted fashion. A novel approach based on pulsed electron heating was proposed by our group as a way to produce electron number densities in excess of 10^{12} cm^{-3} with power requirements two to three orders of magnitude lower than those of conventional DC discharge methods. The proposed method consists in raising the electron number density to approximately 10^{13} cm^{-3} by applying a short high voltage pulse (10 ns duration). After the electron density decays to a predetermined value, say 10^{12} cm^{-3}, a new pulse is applied to ionize the plasma back to 10^{13} cm^{-3}. In air at 2000 K, the interval between consecutive pulses is approximately 10 μs. This approach was demonstrated experimentally with a repetitive pulser system, with 10 ns, 6 kV voltage pulses at repetition rates of about 100 kHz. In these experiments, the electron density was determined by measuring the time varying concentration of the electric conductivity of the plasma, both during the 10 ns pulse and the 10 μs recombination phase. Although this method provides a good assessment of the overall, spatially averaged electron density in the dis-

charge, it is highly desirable a) to confirm this measurement with another independent technique and b) to obtain spatial profiles of the electron number density in the plasma.

Spatially and temporally resolved measurements of the electron number density pose however considerable difficulty. Physical probes tend to disturb the system, while other techniques, such as Thomson scattering and interferometry, do not readily provide accurate quantitative results with high spatial resolution. Therefore, optical techniques that measure ion concentrations are desirable. Of these, emission spectroscopy provides information only on excited species, fluorescence suffers from quenching effects and optical interference that complicate interpretation, and absorption often lacks sensitivity. Cavity ring-down spectroscopy (CRDS), on the other hand, is a sensitive diagnostic tool that was applied earlier in our MURI program to measure the concentrations of N_2^+ ions in a DC plasma discharge [1]. Because N_2^+ is the dominant ion in nitrogen plasmas at our conditions, its concentration can be readily related to the electron number density. The objective of the present work has been to investigate whether this technique could be extended to the case of a pulsed plasma system in which the electron density variations are very fast, of the order of 10 ns during the ionization phase, and 10 μs during the recombination phase. Initial work has been focused on measuring the decaying electron density during the recombination phase.

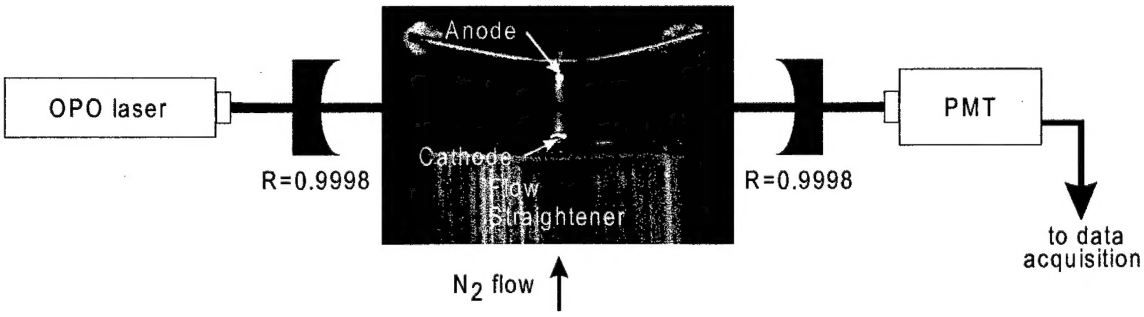

Figure 1. Photograph of the atmospheric pressure nitrogen discharge and schematic diagram of the CRDS set-up. The electrode separation is 0.85 cm, and a current of 180 mA passes through the discharge. The ring-down cavity has a length of 0.75 m, and uses mirrors of 2.54 cm diameter, and 0.5-m radius of curvature. An OPO is used as the ligth source, and a photomultiplier tube (PMT) detects the light exiting the cavity. Beam shaping optics and detection filtering are not pictured.

Figure 1 shows a photograph of the atmospheric pressure nitrogen discharge, as well as a schematic diagram of the CRDS set-up. Nitrogen is injected through a flow straightener and passes through the discharge region with a velocity of about 20 cm/s. The discharge is formed between a pair of platinum pins (separation 0.85 cm) that are vertically mounted on water-cooled stainless steel tubes. The discharge is maintained by a DC current supply (180 mA) in a ballasted circuit (R_b=9.35 kΩ). A 10 kV voltage pulse of 10 ns duration is then superimposed to the DC discharge in order to increase the elec-

tron number density. We study the N_2^+ ion produced by the voltage pulse by probing the (0,0) band of its first negative system ($B\ ^2\Sigma_u^+ - X\ ^2\Sigma_g^+$) in the vicinity of 391 nm. We select this spectral feature because it is comparatively strong and optically accessible. An OPO system (doubled idler) is used as the light source (pulse width ~7 ns, pulse energy ~1 mJ, linewitdth ~ 0.14 cm^{-1}). A 75 cm cavity yields ring-down times of approximately 12 μs, corresponding to mirror reflectivities of about 0.9998 or equivalently about 2500 round-trips by the light inside the cavity. The plasma has strong thermal gradients that tend to destabilize the ring-down cavity: the thermal gradients lead to index-of-refraction changes that alter the course of the beam (similar to a mirage). We find that appropriate selection of cavity geometry is critical to implementation of the CRDS technique. The results reported here use 50 cm radius-of-curvature (ROC) mirrors and a 75 cm length linear cavity, corresponding to a cavity g-parameter of -0.5, where g is unity minus the cavity length divided by mirror ROC. To obtain a spatial profile of the N_2^+ concentration we displace the discharge perpendicularly to the optical axis (i.e., along a direction orthogonal to the plane of Figure 1).

The measured temporal evolution of N_2^+ concentration during the recombination phase following the pulse is shown in Figure 2. We also determine the electron concentration in the discharge by measuring the electrical conductivity of the discharge. We use Ohm's law to compute the product of the average electron number density and column area. The current through the discharge is found by measuring the voltage across the ballast resistor. We measure the potential between the electrodes with high-voltage probes, and then subtract the cathode fall and divide by the electrode separation, to obtain the electric field. For the DC plasma, we find that the ratio of the area-integrated N_2^+ concentration (from CRDS) to the area-integrated electron concentration (from conductivity measurements) is 0.89±0.13. This result agrees with the prediction of our collisional-radiative model that approximately 85% of ions are N_2^+ and the remainder is N^+. We assume that the electron concentration profile has the same shape as the measured N_2^+ profile to determine the centerline electron concentration. The temporally resolved electron concentrations are shown with a swath in Fig. 2. The uncertainty in the DC electron concentration (10%) reflects uncertainties in the area (5%), the momentum transfer cross-section (5%), and the gas temperature (6%). The uncertainty in the time-varying electron concentrations is higher at early times, because as the electric field in the discharge is reduced, the sensitivity to the cathode fall (3% uncertainty) increases. The collisional-radiative model predicts that N_2^+ is the dominant ion produced by the pulse. Thus, the agreement between the time-dependent electron and N_2^+ concentrations during plasma recombination verifies the CRDS measurement. The measured recombination time is consistent with reported (ref. [2], pp. 271-272) dissociative recombination rate coefficients for N_2^+ (approximately 5 x 10^{-8} cm^3/s).

We have demonstrated the use of the CRDS technique to obtain spatially and temporally resolved ion concentrations at the ppm level in a hostile plasma environment. Sub-millimeter spatial resolution and microsecond temporal resolution have been achieved. Plasma behavior is often governed by trace species, such as ions and radicals. Therefore, the measurement technique is well suited for studying plasma dynamics. Fundamentally, the time resolution of the technique is limited by the cavity round-trip time. Shorter cavities with faster detection may be used to study systems that evolve more quickly.

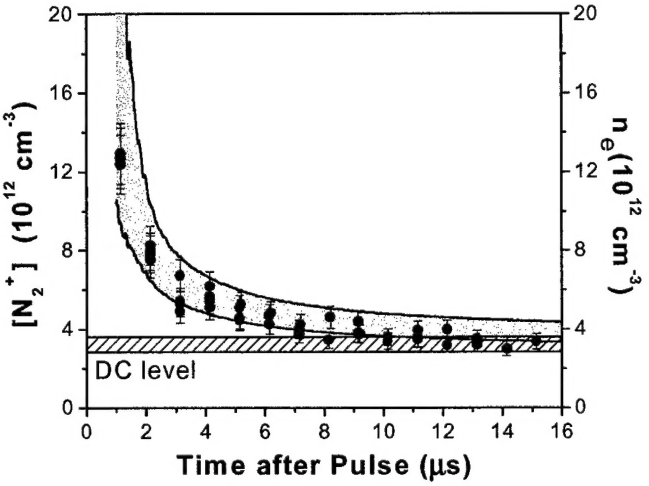

Figure 2. CRDS measurements of N_2^+ concentrations (circles) and conductivity measurements of electron densities (swath) versus time following the firing of a high-voltage pulse in an atmospheric pressure nitrogen DC plasma. The DC level of N_2^+ concentration found by CRDS is shown with a hatched bar.

References:

[1] T. G. Spence, J. Xie, R. N. Zare, D. M. Packan, L. Yu, C. O. Laux, T. G. Owano, C. H. Kruger, and R. N. Zare, "Cavity Ring-Down Spectroscopy Measurements of N_2^+ in Atmospheric Pressure Air Plasmas," presented at 30th AIAA Plasmadynamics and Lasers Conference, Norfolk, VA, 1999.

[2] C. Park, *Nonequilibrium Hypersonic Aerothermodynamics*. New York: Wiley, 1989.